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Influence of overheating criteria in the appraisal of building fabric performance

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Abstract

In response to the threat of anthropogenic climate change, heating dominated countries have focused on reducing the space conditioning demand by increasing insulation and airtightness. However, given climate projections and lifespan of buildings, concerns have arisen on whether these strategies deliver resilient solutions. As overheating can be evaluated through different criteria, this paper investigates if building fabric performance is subject to bias from the assessment method chosen and account for discrepancies between previous studies.

To answer this, we modelled dwellings compliant with 1995 and 2006 UK building regulations and the FEES and Passivhaus standards in a consistent and realistic manner. The parametric study included different weathers, thermal mass, glazing ratios, shading strategies, occupancy profiles, infiltration levels, purge ventilation strategies and orientations, resulting in 16128 simulation models. To provide confidence in the output, the base model was first validated against data collected from a real well-insulated dwelling.

Results show that the benchmark choice is influential in the evaluation of building fabric performance as it is able to inverse overheating trends. Criteria based on adaptive comfort best represented expected behaviour, where improved building fabric is a resilient measure that reduces overheating as long as occupants are able to open windows for ventilation.

Keywords: comfort, overheating, resilience, insulation, building simulation

1 Introduction

Over the last decades, an increasing body of evidence has associated human activities as the drivers of current climate change due to the release of an unsustainable amount of greenhouse gases (GHG) (IPCC 2015). Among these, the building sector accounts for a notorious fraction, especially in the UK, where it represents 45% (Pout and MacKenzie 2012). Thus, numerous initiatives have been adopted to lower and optimise the energy consumption in buildings, particularly since it has been steadily increasing (European Commission 2014). As heating is responsible for 47% of buildings' GHG —16% of UK's total—, there has been a special interest in improving the building fabric, mainly through higher thermal resistance and lower air leakage.

Aligning with the interests for reduced energy consumption that arose after the oil crises, building regulations started to become increasingly strict. New dwellings are now required to achieve transmittances three times smaller than in 1970 (Office of the Deputy Prime Minister 2013a), whereas airtightness is expected to deliver between half to a quarter of the air leakage at that time (Office of the Deputy Prime Minister 2013b; CIBSE 2000). Additionally, several standards have lowered these targets further in the UK, where the Fabric Energy Efficiency Standard (FEES) aims to reduce heat losses by half of what regulations require. Furthermore, the Passivhaus standard (PH) seeks a consumption of $15kWh \cdot m^{-2} \cdot year$, what is about 60% less than FEES.

Another point of concern is that the climate keeps changing (IPCC 2015). Besides global warming, it is considered *virtually certain* that future climate will feature more extreme weather events, specially more severe and longer heat waves (IPCC 2012). These can increase morbidity and mortality as seen in the European heat wave of 2003, where over 14000 persons died inside buildings in France (Vandentorren et al. 2006). Numerous studies have been looking at such experiences to understand and prevent these rates, where they recognised the fundamental role buildings have to alter the final indoor temperature and thus, promoting higher or lower risks. Two fundamental questions arise. Which are the limits of indoor thermal conditions? How building features affect its overheating performance?

Regarding the limits of indoor thermal conditions, a number of criteria have been proposed. These allow researchers and practitioners to quantify overheating, which, in turn, can translate into an evaluation and classification of the performance of existing buildings (Mavrogianni et al. 2012), design strategies (Porritt et al. 2012; McLeod et al. 2013) or potential impact of climate change (de Wilde and Tian 2010). Despite their usefulness, current criteria are not equally developed (Zero Carbon Hub 2015a), they do not identify the same amounts of overheating (Lomas and Kane 2013) and their adoption is voluntary, despite certain clauses in some building regulations (Office of the Deputy Prime Minister 2013a).

At the same time, there has been an increasing amount of research devoted to see if improved building fabric exacerbates temperatures during summertime in heating dominated countries. During the mentioned heat wave, it was found that higher internal temperatures were recorded in rooms without insulation. However, Orme et al. (cited by Dengel and Swainson 2012) linked higher overheating risk with increases of insulation when assessing an update to UK's Building Regulations. The projections of the UKCIP02 allowed, at about the same time, insights of future performance, in which CIBSE (2005) concluded that the performance of increased insulation and reduced air leakage shifts depending on the hourly balance of the building. Subsequent studies have kept proving one possibility or the other, but the particular research questions, scopes, overheating standards, methods and parameters under study do not allow for comparison.

As a result, further research has been requested to clarify the role of improved building fabric together with the overheating criteria currently available (Mylona and Davies 2015; Gupta and Kapsali 2015; Zero Carbon Hub 2015c). The aim of this paper is to review current benchmarks and to perform a holistic assessment of overheating related to building fabric. The hypotheses that will be tested on this study are:

1. 'Different overheating criteria show inconsistent risk trends when evaluating the same buildings'. This will test the robustness of current prediction methods and will detect whether conclusions about building fabric performance can be expressed as their function.
2. 'Dwellings built to meet low targets of heating energy demand develop lower overheating risk but are less robust'. This will characterise the performance according to current knowledge of the drivers of overheating and occupant behaviour.

The study is organised as follows. Firstly, overheating criteria background and development is reviewed. Next, the methods to test the hypotheses are described. Further, overheating criteria are applied to appraise the building fabric performance and discussed. Lastly, key findings are summarised and recommendations for future work are given.

2 Background

There is not yet a widely accepted definition for overheating. Intuitively, it can be said that 'overheating is the raise of a certain temperature over a certain threshold for a certain period of time', where further specification is subject to discussion. In addition, overheating is better expressed as a risk because temperatures depend on the energy exchange in constantly varying circumstances and is subject to occupant psychological evaluation and physiological reactions. According to what is assessed, it relates to health risks, comfort and productivity, of which only the first two are relevant for dwellings (Zero Carbon Hub 2015a).

The knowledge about overheating and health risks is twofold. On the one hand, the relationship on healthy adults is defined in regulations. Here, an implementation of the Wet Bulb Globe Temperature defines the threshold for the 'heat stress index', a metric that integrates all parameters involved. The standard ISO-7243:1989 (British Standards Institution 1994) establishes the reference method, which maintains its approach in the upcoming revision, recently opened for consultation (British Standards Institution 2015). On the other hand, the relationships for vulnerable groups —namely children, elderly and sick people— are not that developed. Despite early warnings of the IPCC (1990), it has not been until more recent experiences of heat waves (e.g. that of France in 2003) and extreme weather events projections that an increasing amount of efforts have focused on this area (Dengel and Swainson 2012). Nonetheless, there is not a framework that clarifies and quantifies these risks in relation to indoor air temperature (Zero Carbon Hub 2015b).

Unlike with health risks, thermal comfort features numerous schemes to assess overheating. Here, it can be reworded as 'an unacceptable level of dissatisfaction due to excessive heat' according to the two main theories of understanding thermal comfort: Fanger's Predicted Mean Vote – Predicted Percentage of Dissatisfied (PMV–PPD) and Adaptive Comfort Models (ACMs). Thus, they can entail explicit temperature thresholds, although it is still a risk. However, the limits of this expectation, duration and severity, do not translate directly from the PMV-PPD or the ACMs, having being proposed a number of overheating criteria based on them. The following sections focus exclusively on the thermal comfort perspective, since known health risk thresholds (i.e. healthy adults) cannot be reached in these circumstances.

2.1 Comfort criteria based on PMV-PPD

Two main standards implement the PMV-PPD model, the ANSI/ASHRAE-55 (2013) and the EN-7730 (British Standards Institution 2005). The only noteworthy difference is that the American regards as acceptable a PPD up to 10%, whereas the European proposes categories based on degrees of satisfaction up to a PPD of 15%. Knowing the typical situations in dwellings, an operative temperature and its dispersion can be worked out. From this, studies have consecutively supported the raising of temperatures to set limits to discomfort, where the main references are CIBSE, Passivhaus and the EN-15251.

CIBSE's TM-36 provides an illustrative fixed threshold for free-running buildings based on PMV-PPD. They argued that an assessment using ACMs —ASHRAE's model was included in the 55-2004 Standard a year ago— "results can be difficult to interpret" (CIBSE 2005 p.9). The criteria rely in setting 'warm' and 'hot' limits —PMV +2 and +3, respectively— by adapting clothing and PPD. A building is said to overheat it 'hot' conditions are met for more than 1% of the occupied time (reasons why 1% not given and the cited 5% for 'warm' is deprecated). Severity is overlooked. The limits for dwellings are derived from research and experiences in offices and schools, as usual. Although precise values for clothing and metabolic activities are not specified, the operative temperature limit in living areas is established to 25°C ('warm', PPD<10%) and 28°C ('hot', PPD<20%). Thresholds for bedrooms are adapted to 21°C and 25°C, respectively, according to what they considered occupant's expectations. However, Humphreys' findings support these values (CIBSE 2006), but the PMV-PPD application would result in 26–27°C due to the lower metabolic activity, provided suitable bedding (0.9met, 0.5–0.7clo). For predictions, the 1% criterion implies the use of Design Summer Years (DSYs) (i.e. third Apr–Sep hottest year on average in 1983–2002) rather than Test Reference Years (TRYs) (i.e. typical year with 1976–1990 average months) so the risk is explicitly taken into account by maximizing it within 'reasonable' limits.

Built on the same grounds, Passivhaus sets the default limit to 25°C (customizable) for a duration up to 10% (compulsory) of the occupied time, implementing findings from Kolmetz (1996) (Passivhaus Institute 2014). Hence, it is stricter for the temperature but more relaxed for the deviation. Here, severity is also overlooked.

The standard EN-15251 (British Standards Institution 2007) proposes a procedure to characterise comfort performance and establishes a time limit for discomfort, applicable to both PMV-PPD and the European ACM. The length of deviation is set, as an example, to 3% or 5%, and it has to be met simultaneously for the occupied periods at year, month, week and day levels. Then, it offers three alternatives to compute occupied hours in discomfort. The first one is a count of the time when comfort is exceeded, as seen before. The second is a degree-hours approach like in HDD-CDD according to the temperature difference ΔT_o over the limit. The third one is a PPD-weighted metric, similar to the previous but using the ΔPPD over the limit as the weighting, more suitable as this parameter does assess comfort. They point out that PPD-weightings yield greater hours, not explaining the causes. Here, they are attributed to the exponential expression of PPD(ΔT_o), common to every thermal comfort model. In fact, it can be seen that each of these methods gives higher results than the previous, potentially discouraging the use of the last two. The category of the building is the highest one that is satisfied in 95% of its spaces. However, this can be misleading as the period and counting method are voluntary, as seen by Nicol and Wilson (2011).

2.2 Comfort criteria based on adaptive models

Likewise, the standards ANSI-ASHRAE 55 (2013) and EN-15251 implement ACMs. The different databases from which they were derived —RP-884 'worldwide' (de Dear et al. 1997) and SCATs 'Europe' (McCartney and Fergus Nicol 2002), respectively—, the methods and the assumptions involved do not allow for a direct comparison (Nicol and Humphreys 2010; de Dear et al. 2013). As explained by de Dear et al. (1997), adaptations under PMV-PPD only accounted for about 50% of the comfort experienced under ACMs, making adaptive models more appropriate for free-running buildings. The ANSI-ASHRAE 55 offers two limits for comfort that result in 80% and 90% acceptability (general and higher comfort, respectively). The EN-15251 gives three qualitative levels —I/II/III— of which the first two coincide in their intended use with the previous standard —80% for II and 90% for I—. Only the EN-15251 suggests how to quantify the performance of the building regarding discomfort, as explained previously. Interestingly, the concept of ACDD for energy demand was not defined nor validated until later on by McGilligan et al. (2011).

CIBSE’s TM-52 (2013) followed research suggestions and recommends the European ACM to appraise overheating in free-running buildings. The background summarises the state-of-the-art of this adaptive model and establishes a limit to overheating inspired in the EN-15251. It is based on three criterions and a building is said to overheat if any two are exceeded. The first one establishes a limit of 3% on the May-September occupied hours for $\Delta T_o \geq 1K$. The second uses the hour-degree method limited to six in any one day. The reasons given for this particular value is that it “is an initial assessment of what constitutes an acceptable limit of overheating” (CIBSE 2013 p.14). The third one is novel and sets 4K limit to severity, which maintains the PPD under approximately 35%. This way, TM-52 catches up with previous critics (e.g. Nicol et al. (2012)). Additionally, it mentions that ACMs should be suitable for dwellings as adaptability premises are truer, despite being derived from offices. Moreover, it reminds that EN-15251 Category I could be used if tighter control is deemed necessary. ACMs' suitability for bedrooms is not discussed, where it might not be applicable as they were devised for a range of 1–1.3met (offices) and sleeping is 0.9. The Guide A (CIBSE 2015) does mention them, setting comfort up to 24°C and an absolute limit of 26°C.

3 Methodology

The appraisal of overheating and building fabric is complex due to two main aspects. Firstly, true limits of discomfort —duration, severity and their relationship— are not yet known, especially in dwellings. Secondly, the need to cover several parameters requires pairwise models to ease the analysis, unlikely to be found in reality. However, these simulations aim to predict *temperatures*, requiring a careful approach (Nicol et al. 2012). Because of this and the need of knowing occupants' perception, thermal comfort research tends to focus on field studies (de Dear et al. 2013).

As a result, the methods for this study are designed to provide a balanced solution. Parametric building simulations implementing different overheating criteria better approach the hypotheses established, while concerns for such techniques are reduced by validating modelling procedures. Thus, a monitored well-insulated dwelling was chosen as the case study and confidence in the parametric simulations is provided based on the reproduction of its performance (sec. 3.3).

3.1 Overheating assessment

The overheating criteria considered are PH, TM-36 and TM-52 to cover limits based on PMV-PPD and ACM theories and given their widespread adoption in both research and construction industry. They establish well-defined thresholds (table 1) for which the following parameters are calculated:

1. **Hours of discomfort:** Count of occupied hours as defined in the criteria.
2. **Weighted hours of discomfort:** Sum of the occupied hours in overheating multiplied by the temperature deviation from the threshold.
3. **Failure rate of rooms:** This set will provide Pass/Fail summary. Additionally, it will indicate whether different criteria yield different trends among them or not.

Table 1: Overview of selected standard overheating criteria

Passivhaus		25°C (customizable)	for	10%	of the occupied time
TM-36	Bedrooms:	25°C	for	1%	of the occupied time
	Living areas:	28°C	for	1%	of the occupied time
TM-52*	Criterion 1:	$\Delta T_{cm,max} \geq 1K$	for	3%	of the occupied time May–Sep
	Criterion 2:	$\Delta T_{cm,max} \cdot time \leq 6$	in		any one day
	Criterion 3:	$\Delta T_{cm,max} \leq 4K$	for		anytime

*Under this benchmark, a building is said to overheat if any two criterions are exceeded.

3.2 Dynamic Simulation Modelling

The base model is a mid-terrace located next to Southampton (UK) built in the late 2000s to meet the Code for Sustainable Homes Level 4 (fig. 1). The election of a terrace is based on that it is the most common dwelling type prone to overheating, being ranked second to flats in overall risk (Palmer and Cooper 2013; Zero Carbon Hub 2015c). In this regard, studies highlight that the key difference between terraces and flats lies in the options for natural ventilation, aspect that is considered as a parameter. Within terraces, research has shown that mid ones are at higher risk for the same reason (Porritt et al. 2012; Gupta and Gregg 2013). The parametric study is done through EnergyPlus (v8.4), a robust tool extensively validated and used in research.

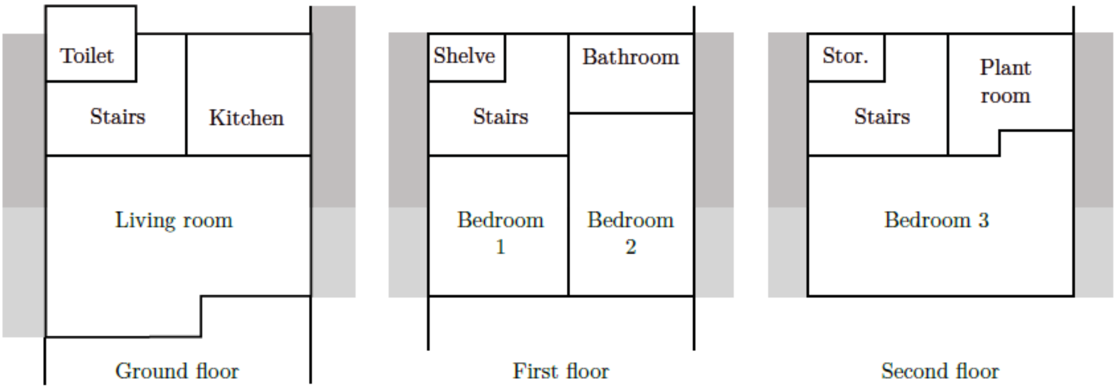


Figure 1: Geometry of the mid-terrace

3.2.1 Base model

The house is modelled to the external side of the thermal envelope following Passivhaus conventions. Each room constitutes a zone to obtain individual temperature readings and to have better control over the definition of heat gains (e.g. the solar distribution model assigns the solar gain to the floor or the room (Ernest Orlando Lawrence Berkeley National Laboratory 2015)). Heating is provided through an ideal loads system to control the energy demand without modelling particular building services, generalizing the results.

The conditions for the elements defining each zone are:

- **Ground floor:** Outdoors, exposed to wind. According to construction details, the house features a suspended floor with a vented cavity.
- **Façades:** Outdoors, exposed to wind and sun.
- **Party walls:** Adiabatic. This simplifies the analysis and is congruent with the study of high insulation levels. Nevertheless, the thermal mass of these walls is still taken into account.
- **Internal walls and floors**: Energy exchanges through these elements are modelled to capture the effect of higher gains in certain rooms (i.e. kitchen and plant room).

3.2.2 Insulation

Studies have associated changes in overheating performance with high insulation levels while they are responsible for substantial space heating energy savings. In order to capture a wide range of building fabric, the modelled cases were dwellings compliant with 1995–2006 regulations and the FEES and Passivhaus standards (table 2). Because they set the context of other parameters (e.g. ventilation systems), this had to be explicitly taken into account in the way the parametric study was carried out (sec. 3.2.11).

Table 2: Definition of the building fabric: U-values and glazing properties

	1995	2006	FEES	PH	Unit
U-value$_{Wall}$	0.45	0.35	0.18	0.10	$Wm^{-2}K^{-1}$
U-value$_{Roof}$	0.25	0.25	0.13	0.10	$Wm^{-2}K^{-1}$
U-value$_{Ground}$	0.45	0.25	0.18	0.10	$Wm^{-2}K^{-1}$
U-value$_{Door}$	3.30	2.20	1.40	0.85	$Wm^{-2}K^{-1}$
U-value$_{Window,limit}$	3.30	2.20	1.40	0.85	$Wm^{-2}K^{-1}$
U-value$_{Window,real}$ (ISO-10292/EN-673)	3.30	2.20	1.30	0.76	$Wm^{-2}K^{-1}$
g-value	0.74	0.70	0.60	0.59	—
Light transmission	0.80	0.76	0.76	0.69	—
Windows layers	4+6+4	4+8+4	4+16+4	5+12+4+12+5	—

3.2.3 Thermal mass

Thermal mass has been identified as a key parameter to assess the influence of insulation and airtightness on overheating. For instance, the Standard Assessment Procedure overheating check depicts a 4K difference between low and high Thermal Mass Parameter (TMP) values (The Concrete Centre 2015). Consequently, three cases were established based on TMP as it takes into account the thermally-active depth of constructions. Lightweight ones are defined as $38KJm^{-2}K^{-1}$ and the medium and heavyweight to 281 and 520, respectively (figures as per ISO-13790 method). To account for dynamic effects, the time step of the simulation was set to 10min as a balance between accuracy and runtime.

Constructions were serialized in three groups, one per thermal mass. Lightweight constructions rely on internal insulation whereas mid and heavyweight rely on internal blocks of different properties and external insulation. Cavities are avoided to simplify the model. The insulation thickness is adapted to the year or standard of construction, according to the remaining thermal resistance. Internal areas and volumes for each of the twelve combinations were worked out and used to override automatic calculations. Thus, energy exchanges are invested in the real enclosed air. Lastly, wall thickness affects the solar heat gain model through reveals of windows, which were designed to keep recesses at 5cm.

3.2.4 Glazing

The original window-to-floor ratio was taken as the base case because the original house was reported to have an adequate winter–summer balance. Variations of ±5% around the baseline were explored by modifying the geometry while keeping shading conditions (fig. 2). Frames and dividers have been considered consistently with the way EnergyPlus takes them into account to keep solar gains constant between building fabrics, while acknowledging changes in U-values (5cm frames in 1995–2006 and 10cm in FEES–PH).

3.2.5 Shading

The knowledge of occupant behaviour (e.g. shading operation) is among the challenges of defining a model because it is still unknown (Mavrogianni et al. 2014). Thus, the original shading based on fixed elements is maintained because it was assessed to provide adequate performance *by default*. Northern devices were updated to meet the same shading angles as the southern ones. However, the bedroom in the loft was modelled with a shading device with optimal operation based on the indoor temperature to approximate good shading conditions because it is completely exposed to the sun. This way shading strategies remain useful regardless the orientation. This 'fully shaded' condition constitutes the best-case scenario whereas the worst one is established with no shading but that of the urban landscape where the same terrace was replicated 15m apart.

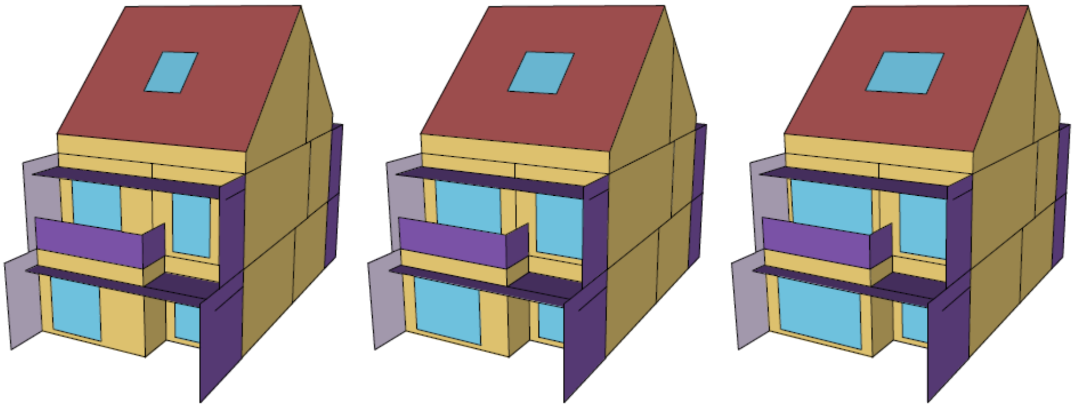


Figure 2: Glazing definition (wall-to-floor glazing ratio)

3.2.6 Internal gains

Likewise shading, two cases have been considered following knowledge limitations. The first is a working family of five members where occupants are away from 9:00 to 17:00. The second is three occupants home all-day-long ('high' and 'low' scenario, respectively).

Occupancy was modelled as discrete individuals in specific rooms. Lighting and other gains such as appliances were based on a customized version of the Passivhaus methodology, informed by UK-specific data and models (Richardson et al. 2010; McLeod et al. 2013; Palmer and Cooper 2013). These established a 'budget' spent accordingly to occupancy, considering residual loads and specific appliances in the kitchen and service rooms. Resulting average gains are 3.83Wm^{-2} and 3.03Wm^{-2} for the high and low scenarios, respectively, considering their respective contributions to the thermal load.

3.2.7 Infiltration

Infiltration has been estimated according to studies, regulations or their specific targets (table 3). To account for wind speed and stack effects, reference infiltrations were translated as permeability in the Walker and Wilson's model, which also considers dwelling geometry, features and suburban exposure. Additionally, flow coefficients were prorated per room according to their external envelope area. To account for the dispersion in airtightness values, high and low scenarios were taken around expected mean values.

Table 3: Infiltration definition of cases (*Data adapted from its original definition)

Construction	Case	q50 [$m^{-3}h^{-1}m^{-2}$]	n [ach]	Data source for reference values
1995	High	30	2.264*	CIBSE (2000)
	Low	10	0.755*	
2006	High	10	0.768*	ODPM (2006b; 2006a)
	Low	5	0.384*	
FEES	High	4	0.337*	ZCH (2009) and ODPM (2013a)
	Low	2	0.169*	
PH	High	0.5*	0.042*	Cotterell and Dadeby (2012)
	Low	0.25*	0.021*	

3.2.8 Ventilation: purge ventilation availability and occupant behaviour

The different years of construction entail particular ventilation systems and modes of operation. These were adapted from regulations and standards to the simulation engine capabilities (table 4). For the considered airtightness in 1995 and 2006, background ventilators are advised, whereas mechanical ventilation (MV) is for FEES and PH, with the latter including a Heat Recovery (HR) section that is by-passed during summertime.

Table 4: Ventilation systems summary

<table>
<tr><th>Case</th><th>CO_2-oriented</th><th>Extract</th><th>Purge</th></tr>
<tr><td>1995</td><td>Background ventilators.
Model: Weather-driven shallow openings.
Operation: Constant.</td><td>Specific Fan.
Model: Extraction fan.
Operation: On-demand, according to internal activity.</td><td rowspan="4">Windows, 20% openable area.
Model: Weather-driven model for wind and stack effect.
Operation: three different behaviours (‘low’, ‘medium’ and ‘high’)</td></tr>
<tr><td>2006</td><td>Background ventilators.
Model: Weather-driven shallow openings.
Operation: Constant.</td><td>Specific Fan.
Model: Extraction fan.
Operation: On-demand, according to internal activity.</td></tr>
<tr><td>FEES</td><td>MV unit.
Model: Ideal system.
Operation: According to 2013 Building Regulations for mechanical systems.</td><td>Extraction to MV unit.
Model: ideal system.
Operation: According to supply. Airflow increased when extraction is greater due to activity.</td></tr>
<tr><td>PH</td><td>MVHR unit.
Model: Ideal system, with HR (by-pass allowed)
Operation: According to Passivhaus standard.</td><td>Extraction to MV(HR) unit.
Model: ideal system.
Operation: According to supply. Airflow increased when extraction is greater due to activity.</td></tr>
</table>

Real window opening behaviour is not yet well-known for building simulation purposes. As each of the overheating criteria suggests limits of discomfort, it has often been modelled to satisfy their requirements, assuming that occupants would take actions to prevent excessive overheating. Although this premise is exclusive of adaptive comfort, it has been taken into account for PH and TM-36 criteria as a traditional assumption in previous studies. Therefore, windows are opened if the following conditions are met simultaneously:

1. A trigger temperature is surpassed.
2. The external temperature is lower than the internal.
3. There are occupants in the house.

Because in adaptive comfort the first condition depends on the external running mean, the temperature trigger was implemented through hourly schedules calculated for each case. To study the impact of purge ventilation, three availability scenarios were studied:

1. **Low:** Purge ventilation is never available. This constitutes a worst-case scenario for control purposes.
2. **Medium:** Purge ventilation is available during daytime if there are occupants in the dwelling. The trigger temperature is established according to each overheating criteria as the threshold for overheating.
3. **High:** Purge ventilation is always available as long as there are occupants. This constitutes a best-case scenario where occupants optimize window opening behaviour. Here, occupants aim to maintain the neutrality temperature. Because in PMV-PPD this temperature would be the same, PH was modelled to 23°C and TM-36 to 25°C during the day and 21°C during the night.

3.2.9 Orientations
Four cases, one per cardinal point, were modelled to approach results in any orientation.

3.2.10 Location and future projection
London was taken as the reference location. Due to the known problems with DSYs weather files, TRYs were used to carry out the simulations (Jentsch et al. 2014). To explore performance under higher external temperatures and approach the resilience of different building fabrics, the climate change projection given by Eames et al. (2011) for 2080 (high emissions scenario, 90% percentile) was considered.

3.2.11 Conditional assemblies
The appraisal of a wide range of building fabrics entails different conditions and systems for each building model. Following the capabilities of EnergyPlus, components were defined in separate files and only relevant combinations were assembled for the simulation. For instance, ventilation featured conditions based on regulations and standards (system type and capacity), occupancy (availability) and purge strategy (parameter and overheating criteria). Altogether, these generate 16128 computational models.

3.3 Validation
The adequacy of modelling techniques is appraised through internal temperatures on free-running mode and the space heating energy demand. The first is aimed specifically to overheating performance and it is based on the original house specifications (table 5), real occupancy derived from sensors and simulation with the real external conditions. The latter were recreated from official weather stations given the limitations of on-site external measurements (Met Office 2015; World Meteorological Organization 2015).

Table 5: Base case general properties

Building Fabric	Opaque transmittances	0.11–0.15 $Wm^{-2}K^{-1}$
	Windows transmittances	0.78–1.24 $Wm^{-2}K^{-1}$
	Thermal Mass Parameter	250 $KJm^{-2}K^{-1}$
	Window-to-floor ratio	21%
	Airtightness	1.25ach@50Pa
MVHR unit	Airflow capacity	0.50ach
	Consumption	13.2kW $m^{-2}y^{-1}$
	Heat Recovery	77%

Norms were taken to appraise the goodness of fit between the real and the simulated time series (fig. 3). The 2-norm was used as the indicator of the average dissimilitude between signals, which, divided by that of the real one, resulted in deviations of 2.4% (≈0.6K). Similarly, the ∞-norm was taken as the indicator of the peak dissimilitude, being 6.1% (≈1.6K). Given the number of uncertainties, simplifications and assumptions in the process, these have been interpreted as a reasonable guarantee of the validity of the simulation. However, they are high enough to prevent accurate absolute values for a study in overheating and the results of the study will necessarily depend on the ranking of figures.

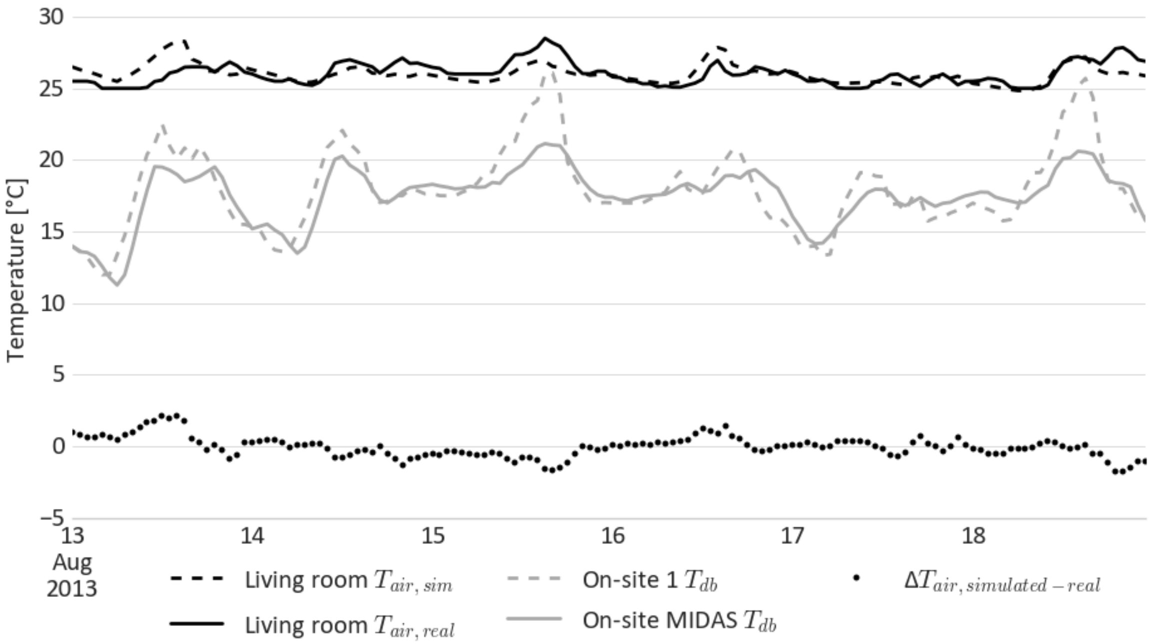


Figure 3: Validation of the overheating model: typical summer week

The validation of space heating demand ensures that simulations under the current weather are within reasonable limits (fig. 4). This is done comparing the space heating demand intensity of the simulations with the heating energy consumption of the UK stock or FEES and PH goals. The heating energy consumption takes into account domestic hot water (DHW) and the efficiency of the equipment. Considering that DHW is about 30% of the demand and a boiler efficiency of 85%, values would be 1.5 times greater, in the range of known values (Palmer and Cooper 2013; BRE 2005). On the contrary, FEES and PH directly specify their heating energy demand, being the average of the locations close to the goals of $39\text{kWh}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$ and $15\text{kWh}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$, respectively. It must be considered that FEES and PH achieve their goals by an iterative design process, meaning that the dispersion in the demand is due to the propagation of cases that have not been optimized to satisfy them.

Figure 4: Space heating energy demand intensity

4 Results and discussion

Overheating criteria appraise performance based on annual indicators, which have been computed coherently with the simulations. The exception is when purge ventilation is not available as there is no occupant behaviour involved. Here, each benchmark was applied directly to the results. Data has been stratified in equally sized samples according to the parameters of interest for each indicator, namely purge strategy, overheating criteria (linked to the opening behaviour modelled), weather, and building fabric.

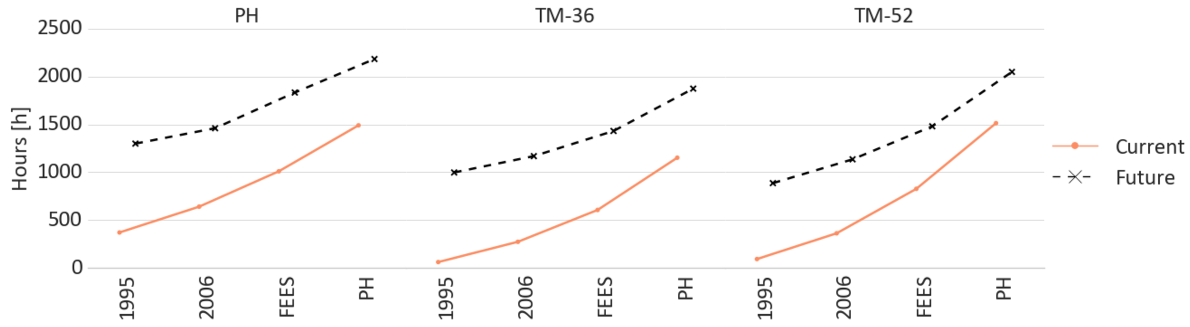
The analysis relies on pairwise comparisons given the hypotheses, the way simulations were generated and the outcome of the validation. Hence, results are presented through the average of each subset (over 5000 observations). Because rooms with very different occupancies are summarized together in this assessment, absolute figures cannot be translated directly to specific cases. Finally, each group is analysed through the Kruskal-Wallis test to appraise whether the changes observed are statistically significant or not. These are followed by the Nemenyi post-hoc tests to see which construction pairs within the same group are significantly different, if any.

4.1 Hours in discomfort

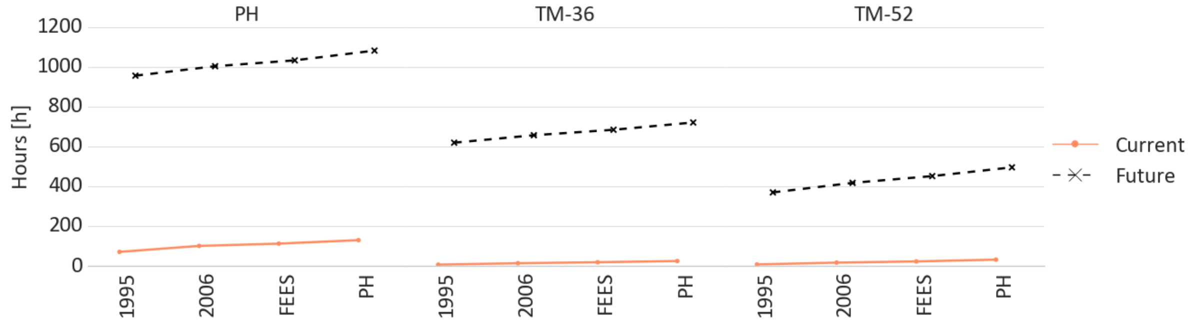
The results show the variation of overheating hours for different purge ventilation strategies and weathers (fig. 5, table 6). When windows cannot be opened ('low' scenario) the risk is significantly higher, reaching maximums over 2000h (≈23% of the year). The values for each overheating benchmark differ quantitatively, as known, but with an unusual ranking. PH yields more hours than TM-36 as it could be expected from the temperature thresholds, but for TM-36 and TM-52, the latter tends to report higher values for the current weather. This is due to the definition of the thresholds and the TRY weather file. The TM-36 defines an absolute limit of 28°C whereas the TM-52 focuses on the ΔT over the running mean. Thus, the TM-36 would result in fewer hours under circumstances prone to overheating as this one in a mild weather. For 1995, infiltration levels at 0.75–2.24ach provide a major cooling mechanism because it is the only option available. Contrarily, the mechanical ventilation and infiltration in a PH gives about 0.40 and 0.02–0.04ach, respectively. The result is that criteria show that improved building fabric develops higher overheating in every case. Nevertheless, overall figures suggest that this situation would be unbearable for occupants with the exception of 1995 dwellings under current weather.

The case where windows can be opened during daytime aimed to represent a 'medium' scenario where occupants, assuming a behavioural model inferred from the benchmarks, take action to keep rooms just below the thresholds. Here, absolute values are several times lower, ranging 8-180h and 400–1100h for current and future weather, respectively. Criteria now follow the ranking reported by previous studies, highlighting the advantages of adaptation for the climate change scenario. Improved building fabric also results in more hours above the threshold although the slope of the curve has diminished remarkably.

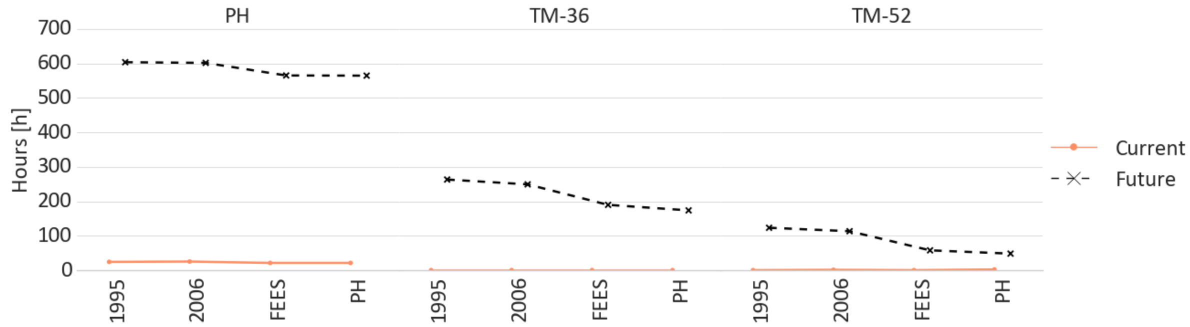
In contrast, when occupants are expected to restore neutrality, the risk diminishes over 50% and every benchmark reports benefits from higher levels of insulation and airtightness. The temperature trigger for opening windows is lower than the threshold and indoor conditions are kept as neutral as comfort and occupancy allow. The TM-52 evaluation reports values fewer than 150h (≈1.7% of the year) for the future weather. Combined with the previous result, this indicates that there is still great potential for comfort in occupant adaptation and the external temperature daily swing. Now, improved envelopes are always beneficial although not necessarily significant between 1995 and 2006 or FEES and PH.



a) Purge ventilation 'Low'



b) Purge ventilation 'Medium'



c) Purge ventilation 'High'

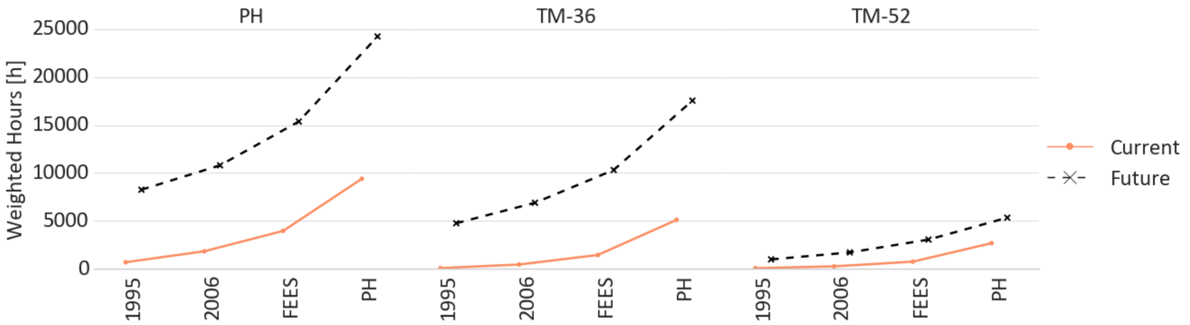
Figure 5: Mean overheating hours (Y-axis adapted per strategy)

4.2 Weighted hours in discomfort

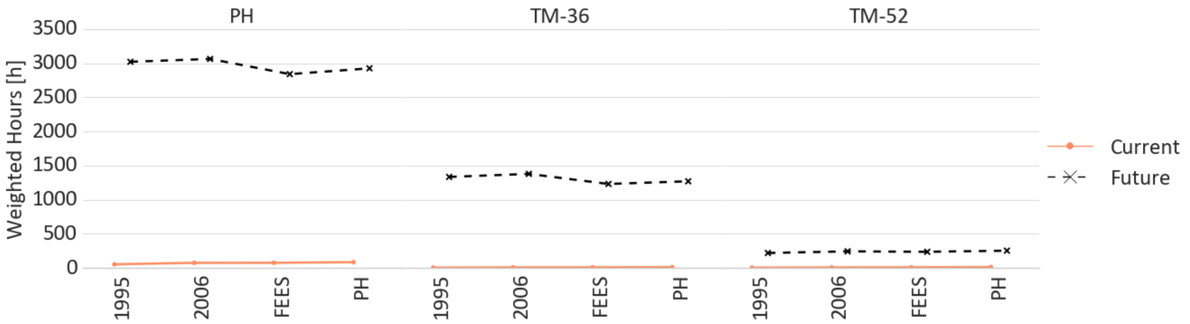
Weighted hours are only considered in the TM-52, although they have been widely used to account for severity with a single value. The outcome provides a different perspective on what the hour count seemed to suggest (fig. 6). The ranking of the criteria is consistent with other studies and stresses the harmful effects of sealing up dwellings when windows are kept shut. However, results for TM-52 show values several times lower even though indoor temperatures are above the threshold as often as in the other cases. Therefore, this overheating is due to lower ΔT, being about one for 1995 and two for PH.

Weighted hours show different trends than before for the 'medium' purge strategy. The PH threshold of 25°C in the current weather shows increasing overheating, from 85h in 1995 to 116h in PH. It decreases in the future from 3572h to 3437h, respectively, although only the reductions experienced by FEES are statistically significant (table 7). TM-36 experiences the same results as PH whereas in the TM-52 trends keep growing but at a slower rate than before. Overall, the response is not the same when the maximum comfort temperature allowed varies. The comparison with the values obtained in the hour count shows that houses with a PH-based window opening algorithm had an average ΔT of 3, TM-36 of 2 and TM-52 lower than 1. Hence, FEES and PH achieve lower overheating for high external temperatures since 1995 and 2006 reported higher weighted hours despite being less time over the thresholds, situation that does not take place in TM-52 due to its ΔT.

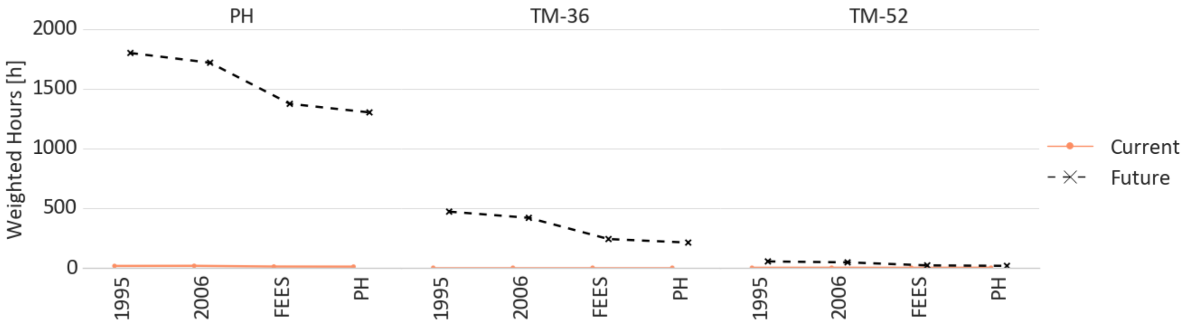
Previous considerations towards the maximum comfort temperature also arise in the 'high' purge ventilation strategy. Aiming for neutrality improves the behaviour of better building fabric but the specific temperatures generate similar ΔT. Altogether, these results indicate that FEES and PH stabilise temperatures in a smaller range than the others. They report less overheating for large deviation from their limits, but not for the small ones. Additionally, they improve results if they are given margin as in the 'high' case. 1995 and 2006 benefit from higher infiltration and conduction when the weather is colder than their thresholds, but they are no longer beneficial given the temperature increment in 2080.



a) Purge ventilation 'Low'



b) Purge ventilation 'Medium'

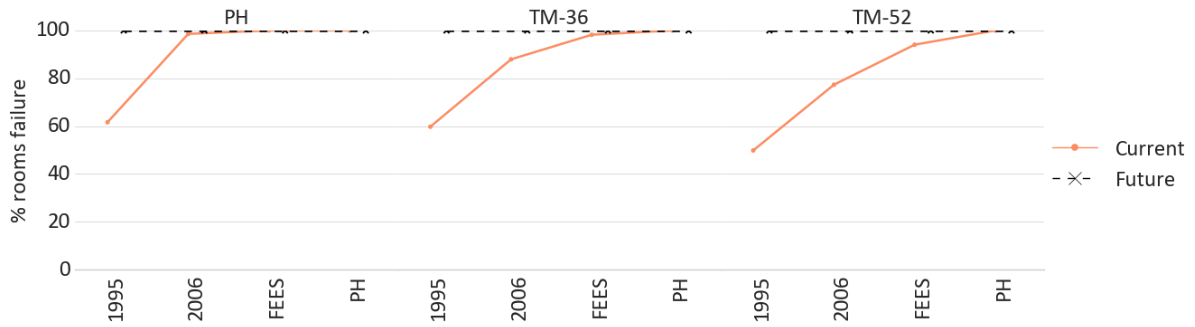


c) Purge ventilation 'High'

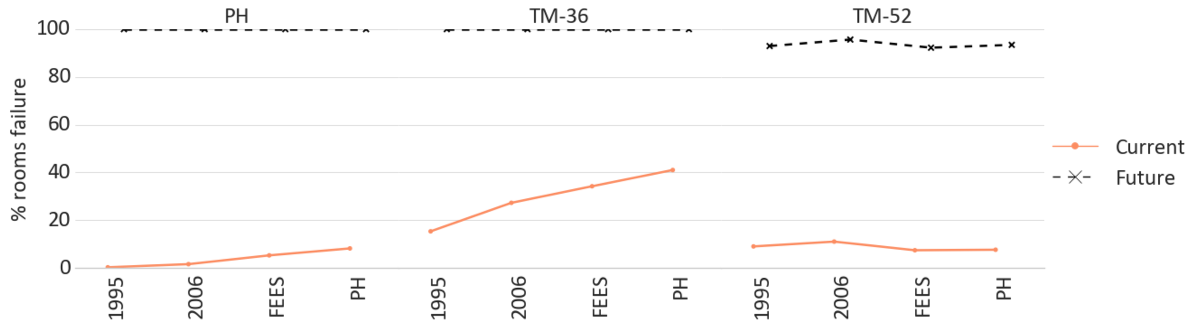
Figure 6: Mean overheating weighted hours (Y-axis adapted per strategy)

4.3 Overheating criteria

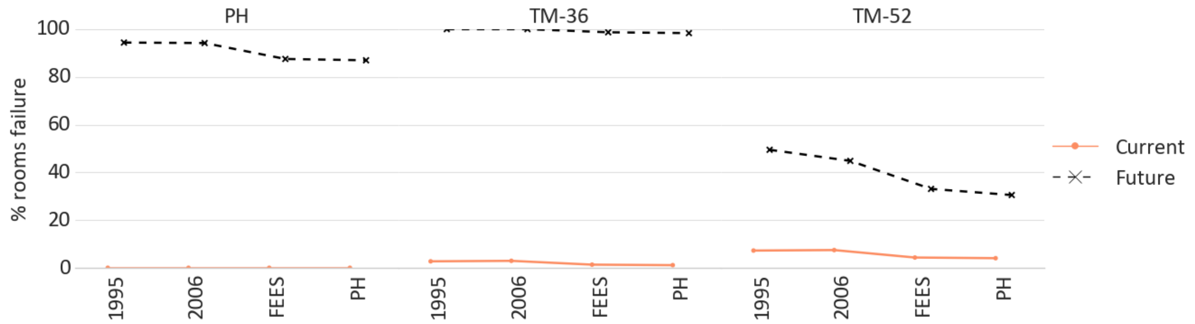
Figure 7 shows the overall results of the benchmarks. It has to be considered that the approach through extreme cases —low-high parameter values— make large proportions of the simulations prone to overheating. The lack of purge ventilation shows a steep evolution towards 100% for current weather as building fabric changes and a complete failure for the future scenario. The only noteworthy difference is that TM-52 depicts lower values than TM-36 despite figures obtained in the hour count. The reasons are that TM-52 implements three criterions of which two need to be failed to report overheating. Moreover, the hour count is done for ΔT≥1 and the other two allow for restrained deviations, even though the maximum comfort threshold is met before 28°C.



a) Purge ventilation 'Low'



b) Purge ventilation 'Medium'



c) Purge ventilation 'High'

Figure 7: Percentage of room per group failing their overheating criteria

Inconsistencies and limitations between criteria are evident in subfigure 7-b. PH and TM-36 report trends as in the hour breakdown, but now TM-36 has a higher failure rate under current weather. This is because the relationship between the temperature limit and the amount of time is unfavourable (28°C–1% of the occupied time against 25°C–10%). Remarkably, and unlike the previous, TM-52 captures reductions in the risk with improved building fabric under current climate. Nevertheless, only those by FEES are statistically significant in the future scenario (table 8). These results contrast with the indicator breakdown shown earlier because small overheating is neglected in TM-52. This further reinforces that FEES and PH tend to maintain better indoor temperatures for $\Delta T \geq 1$ whereas they are more sensitive to smaller ones. Lastly, 'high' purge ventilation results also support these conclusions. The temperature offset from the maximum threshold not only lowers the risk substantially but also inverses trends in PH and TM-36 while demonstrating the effectiveness of better building envelopes.

5 Conclusions

Given past experiences of heat waves and the projections of climate change, researchers and practitioners need to be able to quantify their impact in the thermal environment. However, there is a lack of agreement in the methods to use. At the same time, the role of building fabric in overheating risk has been subject of numerous studies that have arrived at apparently contradictory conclusions. This paper has examined the criteria provided by Passivhaus and CIBSE to appraise the performance of four building envelopes and tested their coherence and suitability in the quantification of overheating.

The results demonstrate that available criteria can identify different overheating trends, depending on the considered occupant window opening behaviour and constructions. The TM-52 is deemed the most appropriate among the benchmarks considered because it was specifically derived from comfort evaluations in free running buildings and recommends sensible limits to duration and severity of discomfort. Nonetheless, none of them seem advisable as the only metric to appraise performance and further efforts are deemed necessary to improve the evaluation and communication of overheating risk. Moreover, it remains essential a better understanding of the properties of discomfort and health risks as assessment procedures relies heavily on them.

Results regarding overheating and building fabric are twofold. The combination of insulation, airtightness and ventilation for 1995 translates in lower overheating risk when purge ventilation is not available since the external temperatures are below the maximum comfort threshold most of the time. However, better building fabric arises as the best option against severe overheating or when windows are operated to reach the neutrality temperature in both current and future climates. Although further studies should extend these findings to other dwelling types, they suggest that the goals of lowering carbon emissions and the delivery of resilient and comfortable dwellings can align through improved building fabric.

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7 Appendix

Table 6: Significance of statistical tests for hour count in figure 5

Purge	Standard	Weather	Kruskal-Wallis	2006-1995	FEES-1995	PH-1995	FEES-2006	PH-2006	PH-FEES
Low	PH	Current	***	***	***	***	***	***	***
Low	PH	Future	***	***	***	***	***	***	***
Low	TM-36	Current	***	***	***	***	***	***	***
Low	TM-36	Future	***	***	***	***	***	***	***
Low	TM-52	Current	***	***	***	***	***	***	***
Low	TM-52	Future	***	***	***	***	***	***	***
Medium	PH	Current	***	***	***	***	***	***	***
Medium	PH	Future	***	**	***	***	*	***	*
Medium	TM-36	Current	***	***	***	***	***	***	***
Medium	TM-36	Future	***	***	***	***	**	***	**
Medium	TM-52	Current	***	***	***	***	**	***	***
Medium	TM-52	Future	***	***	***	***	***	***	***
High	PH	Current	***			.	*	**	
High	PH	Future	***		***	***	***	***	
High	TM-36	Current	***		***	***	***	***	
High	TM-36	Future	***		***	***	***	***	
High	TM-52	Current	***			***		***	***
High	TM-52	Future	***		***	***	***	***	

p-values: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05 ≤ . < 0.1

Table 7: Significance of statistical tests for weighted hours in figure 6

Purge	Standard	Weather	Kruskal-Wallis	2006-1995	FEES-1995	PH-1995	FEES-2006	PH-2006	PH-FEES
Low	PH	Current	***	***	***	***	***	***	***
Low	PH	Future	***	***	***	***	***	***	***
Low	TM-36	Current	***	***	***	***	***	***	***
Low	TM-36	Future	***	***	***	***	***	***	***
Low	TM-52	Current	***	***	***	***	***	***	***
Low	TM-52	Future	***	***	***	***	***	***	***
Medium	PH	Current	***	***	***	***		**	**
Medium	PH	Future	***		**		***	**	
Medium	TM-36	Current	***	***	***	***	.	***	***
Medium	TM-36	Future	***	.	*		***	*	
Medium	TM-52	Current	***	***	***	***	*	***	***
Medium	TM-52	Future	***	***	***	***		*	**
High	PH	Current	***		**	***	***	***	
High	PH	Future	***		***	***	***	***	
High	TM-36	Current	***		***	***	***	***	
High	TM-36	Future	***	.	***	***	***	***	
High	TM-52	Current	***			***		**	***
High	TM-52	Future	***		***	***	***	***	

p-values: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05 ≤ . < 0.1

Table 8: Significance of statistical tests for percentage of rooms failing in figure 7

Purge	Standard	Weather	Kruskal-Wallis	2006-1995	FEES-1995	PH-1995	FEES-2006	PH-2006	PH-FEES
Low	PH	Current	***	***	***	***			
Low	PH	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Low	TM-36	Current	***	***	***	***	***	***	
Low	TM-36	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Low	TM-52	Current	***	***	***	***	***	***	**
Low	TM-52	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Medium	PH	Current	***		***	***	***	***	***
Medium	PH	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Medium	TM-36	Current	***	***	***	***	***	***	**
Medium	TM-36	Future	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Medium	TM-52	Current	**				**	*	
Medium	TM-52	Future	**	*			**		
High	PH	Current	n/a	n/a	n/a	n/a	n/a	n/a	n/a
High	PH	Future	***		***	***	***	***	
High	TM-36	Current	***		.	*	*	**	
High	TM-36	Future	***		***	***	***	***	
High	TM-52	Current	***		*	**	**	**	
High	TM-52	Future	***	.	***	***	***	***	

p-values: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05 ≤ . < 0.1